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(54) **SENSORLESS ELECTRIC MACHINE**

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(71) Applicant: **General Electric Company**,  
Schenectady, NY (US)

(72) Inventors: **Kum Kang Huh**, Niskayuna, NY (US);  
**Patel Reddy**, Hyderabad (IN); **Ayman**  
**Mohamed Fawzi El-Refaie**, Niskayuna,  
NY (US); **Patrick Lee Jansen**, Scotia,  
NY (US); **Roy David Schultz**, Erie, PA  
(US); **Lembit Salasoo**, Schenectady, NY  
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(73) Assignee: **General Electric Company**, Niskayuna,  
NY (US)

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*Primary Examiner* — Hanh Nguyen

(74) *Attorney, Agent, or Firm* — Joseph J. Christian

(65) **Prior Publication Data**

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(57) **ABSTRACT**

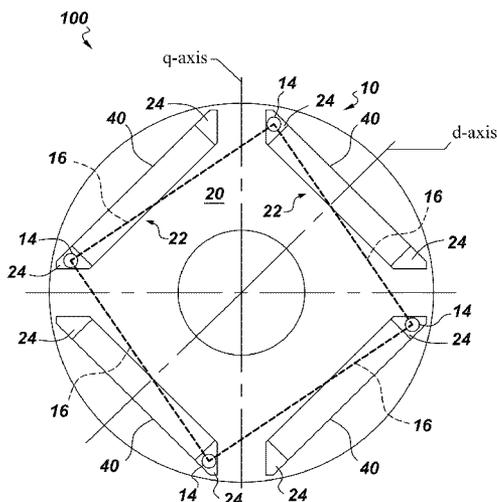
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**H02K 1/24** (2006.01)  
**H02K 29/12** (2006.01)  
**H02K 1/22** (2006.01)  
**H02K 1/27** (2006.01)

An electric machine that includes a rotor core made of mag-  
netic steel; a stator configured with stationary windings  
therein; openings disposed within or on the rotor core; and a  
rotor circuit that is configured to introduce saliency based on  
an orientation of part of the rotor circuit in relationship to a  
pole location of the electric machine, where the rotor circuit is  
made of a conductive, non-magnetic material. A rotor com-  
ponent and various embodiments of electric machines are  
also disclosed. The present invention has been described in  
terms of specific embodiment(s), and it is recognized that  
equivalents, alternatives, and modifications, aside from those  
expressly stated, are possible and within the scope of the  
appending claims.

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CPC ..... **H02K 1/246** (2013.01); **H02K 1/223**  
(2013.01); **H02K 29/12** (2013.01); **H02K 1/276**  
(2013.01)

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USPC ..... 310/156.74, 156.75, 156.76, 181  
See application file for complete search history.

**19 Claims, 16 Drawing Sheets**



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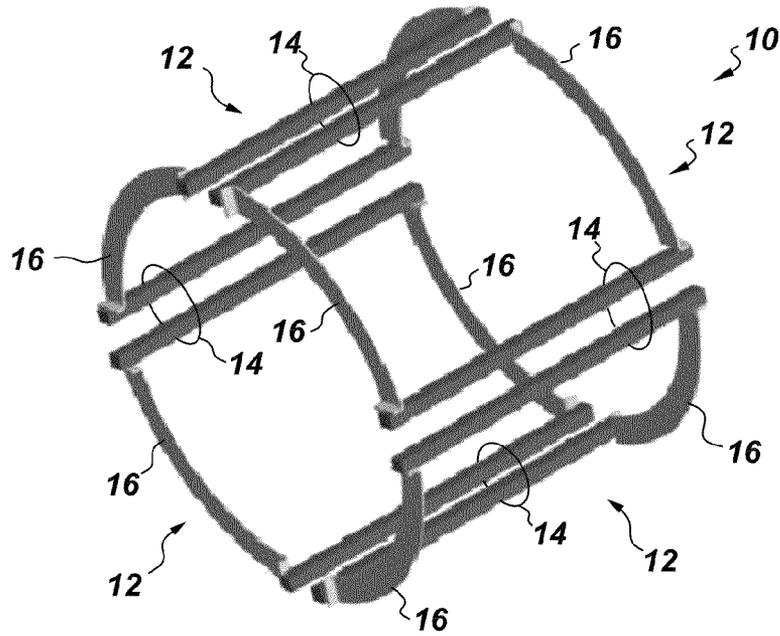
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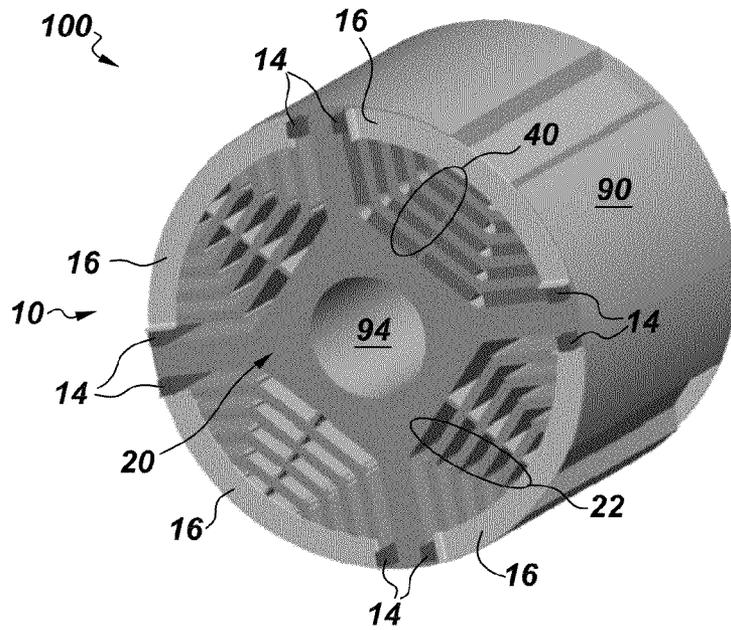
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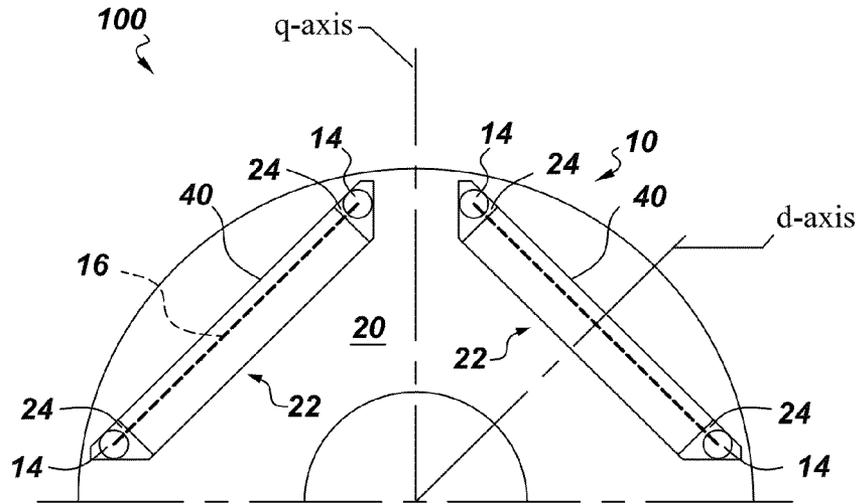
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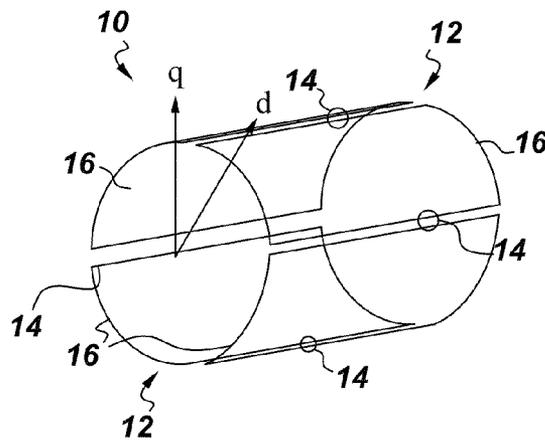
*Fig. 1*



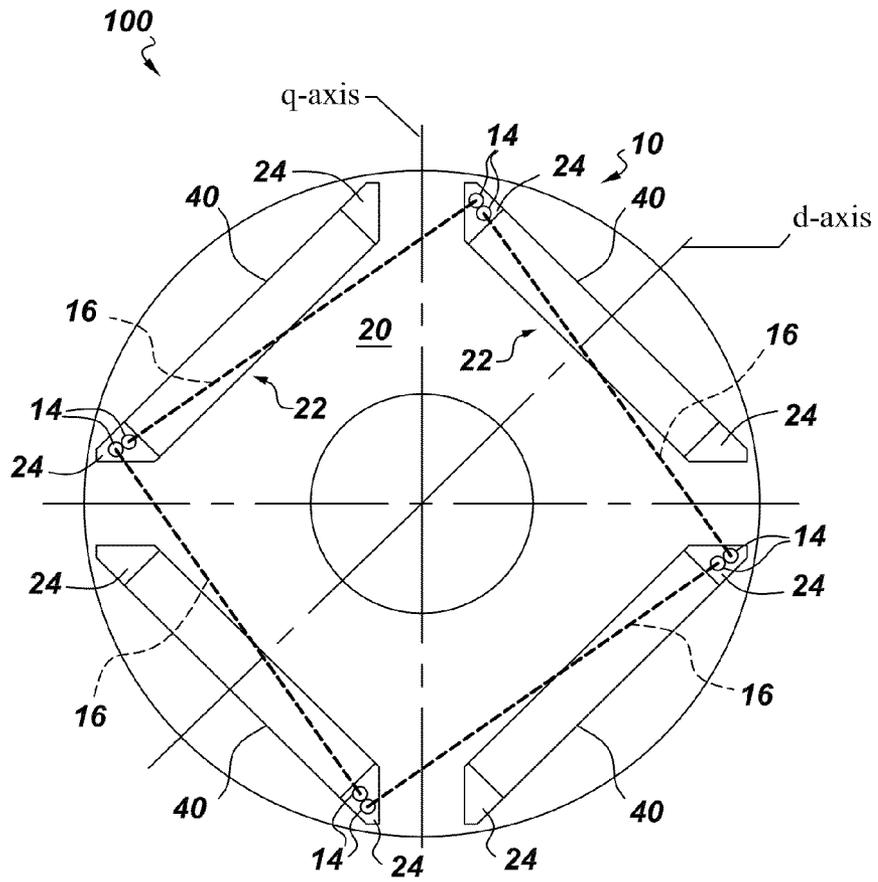
*Fig. 2*



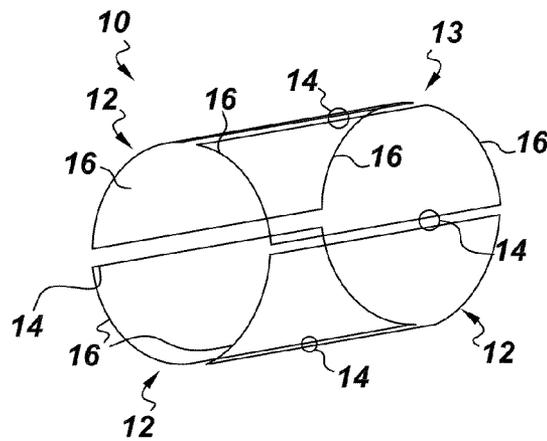
*Fig. 3A*



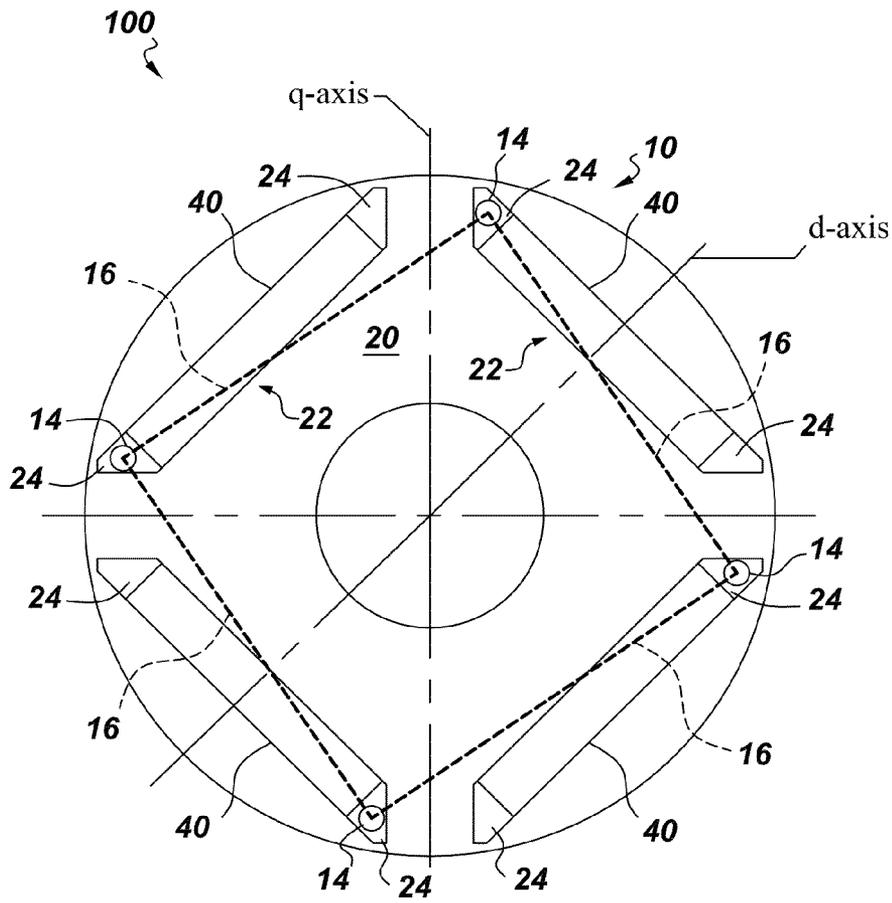
*Fig. 3B*



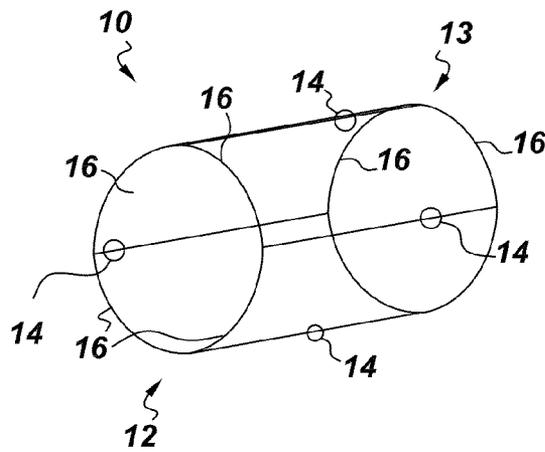
**Fig. 4A**



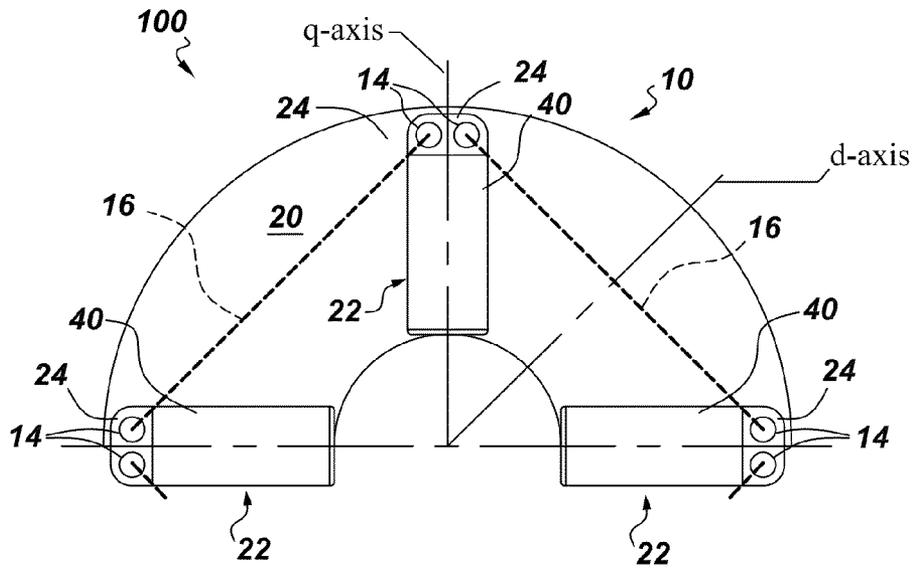
**Fig. 4B**



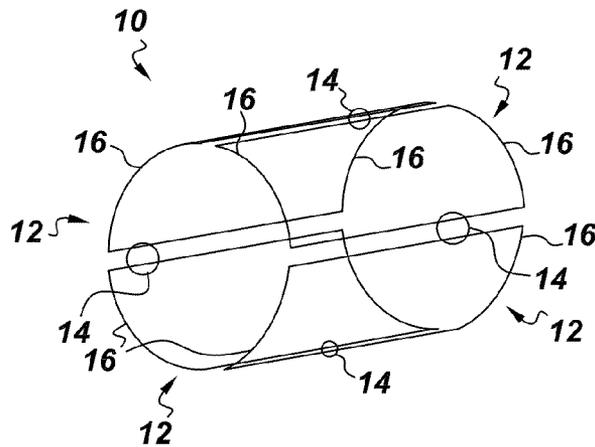
**Fig 5A**



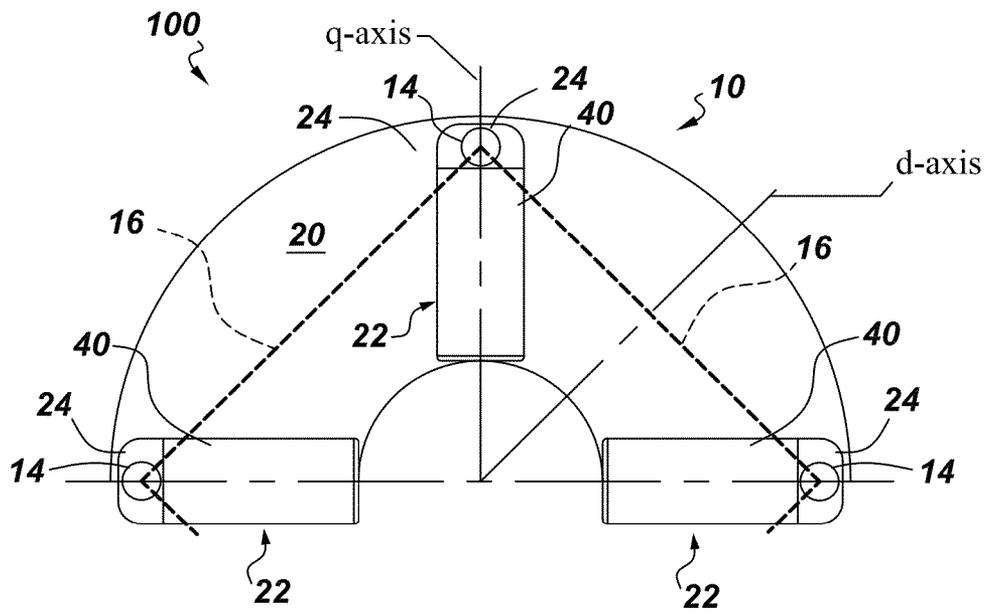
**Fig. 5B**



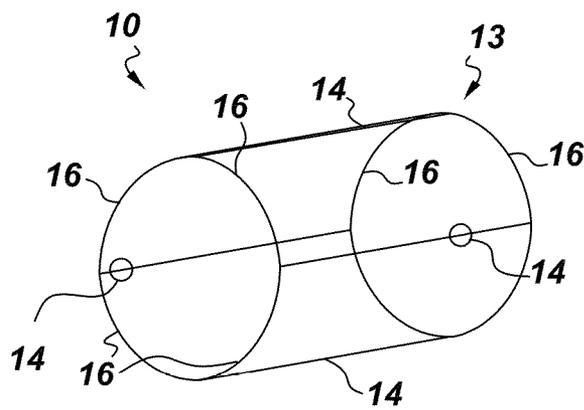
**Fig 6A**



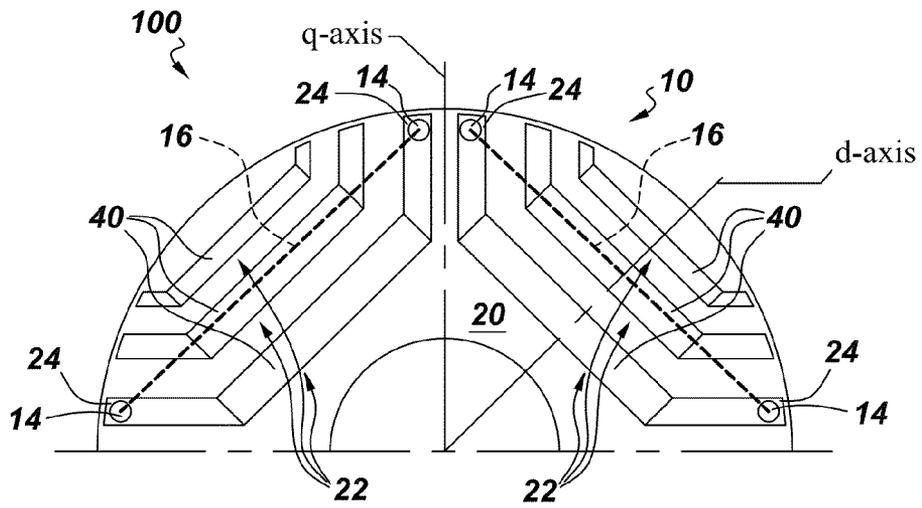
**Fig. 6B**



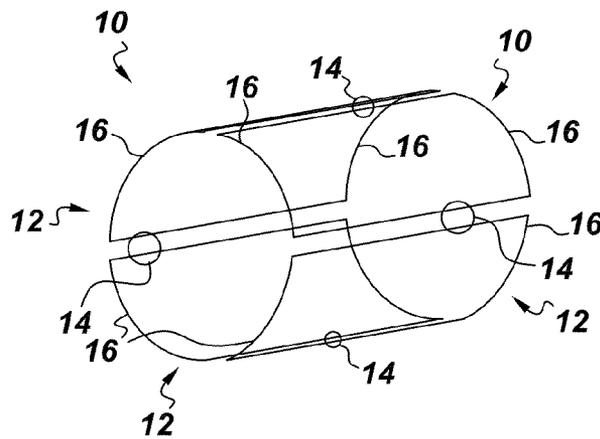
**Fig 7A**



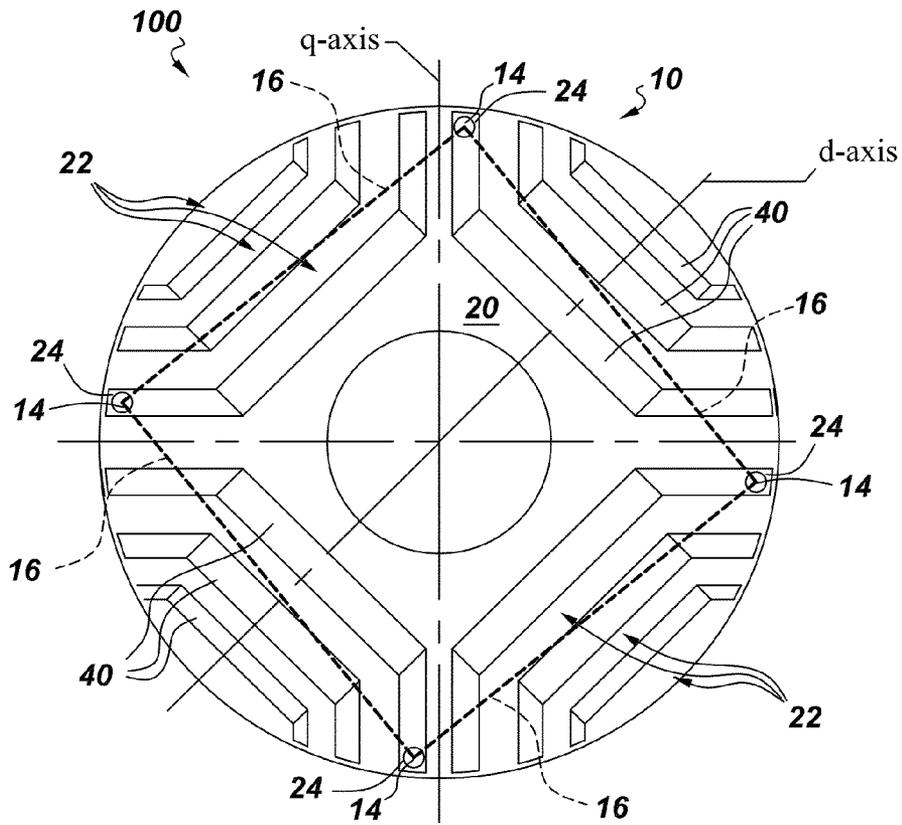
**Fig. 7B**



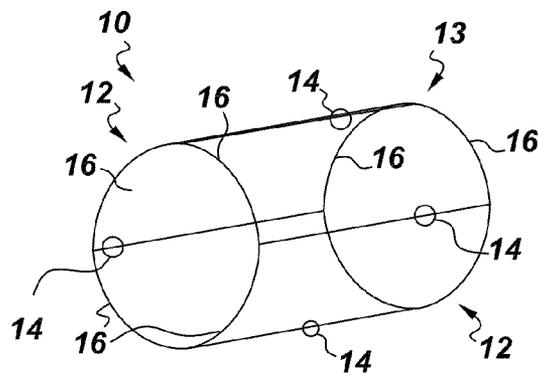
*Fig 8A*



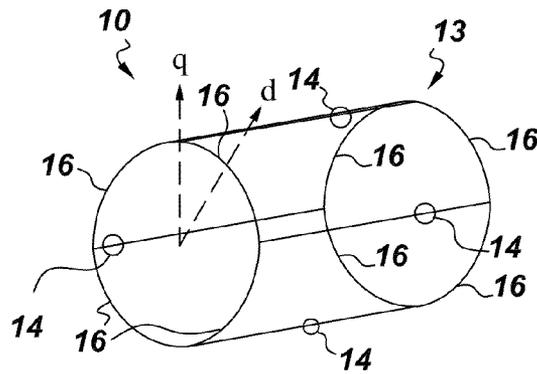
*Fig. 8B*



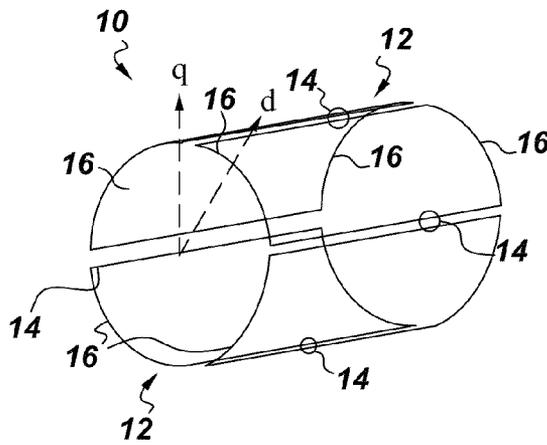
**Fig 9A**



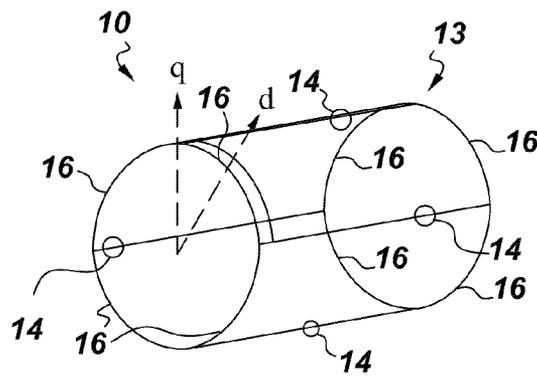
**Fig. 9B**



*Fig. 10A*



*Fig. 10B*



*Fig. 10C*

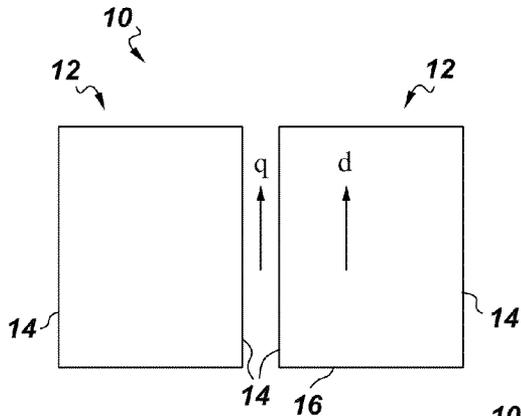


Fig. 11

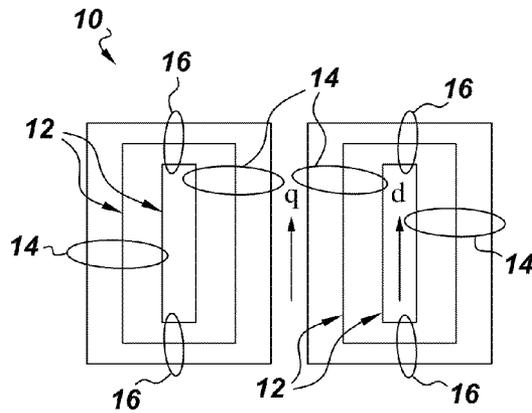


Fig. 12A

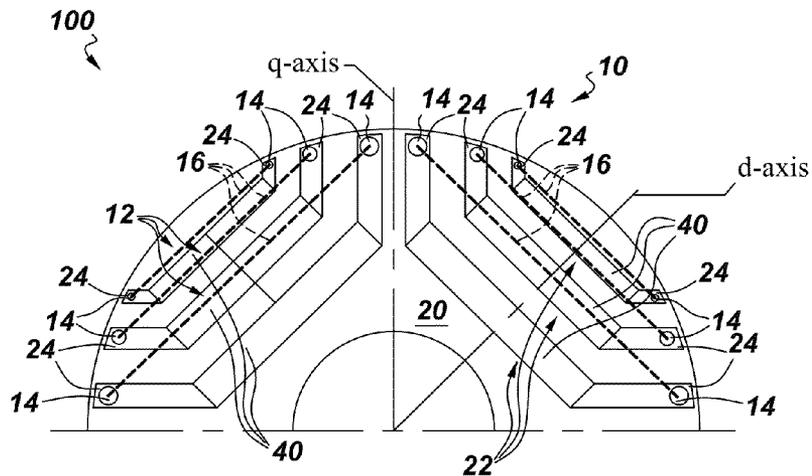


Fig. 12B

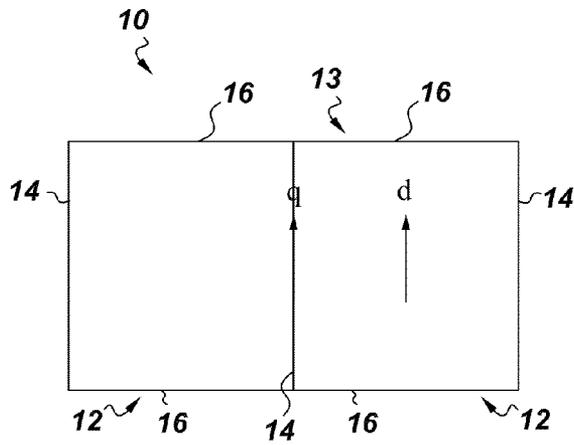


Fig. 13

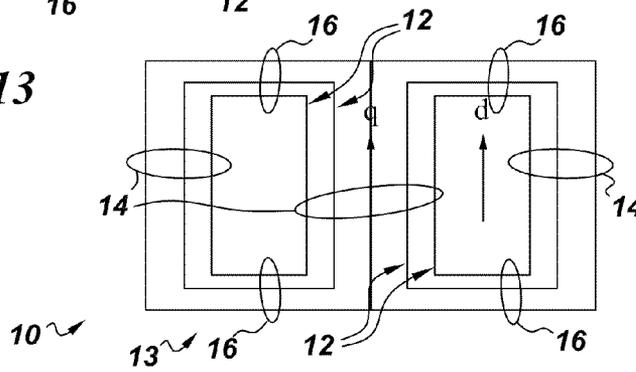


Fig. 14A

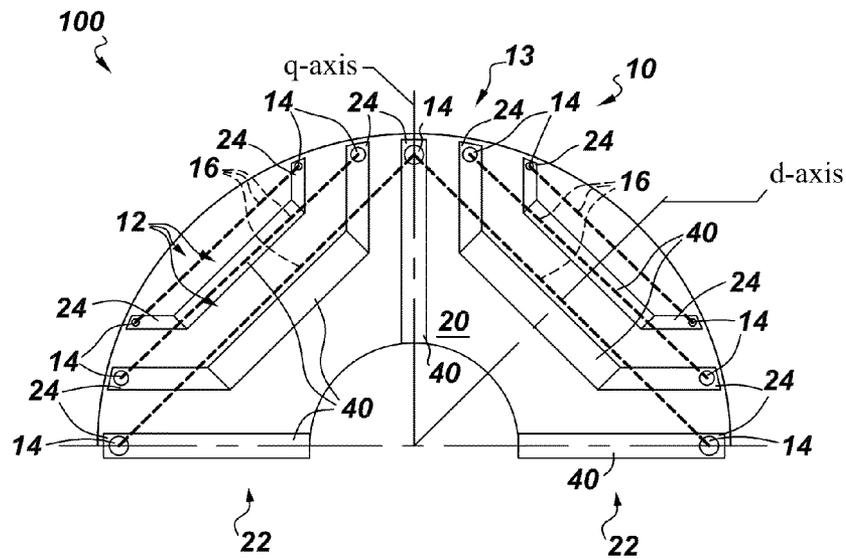


Fig. 14B

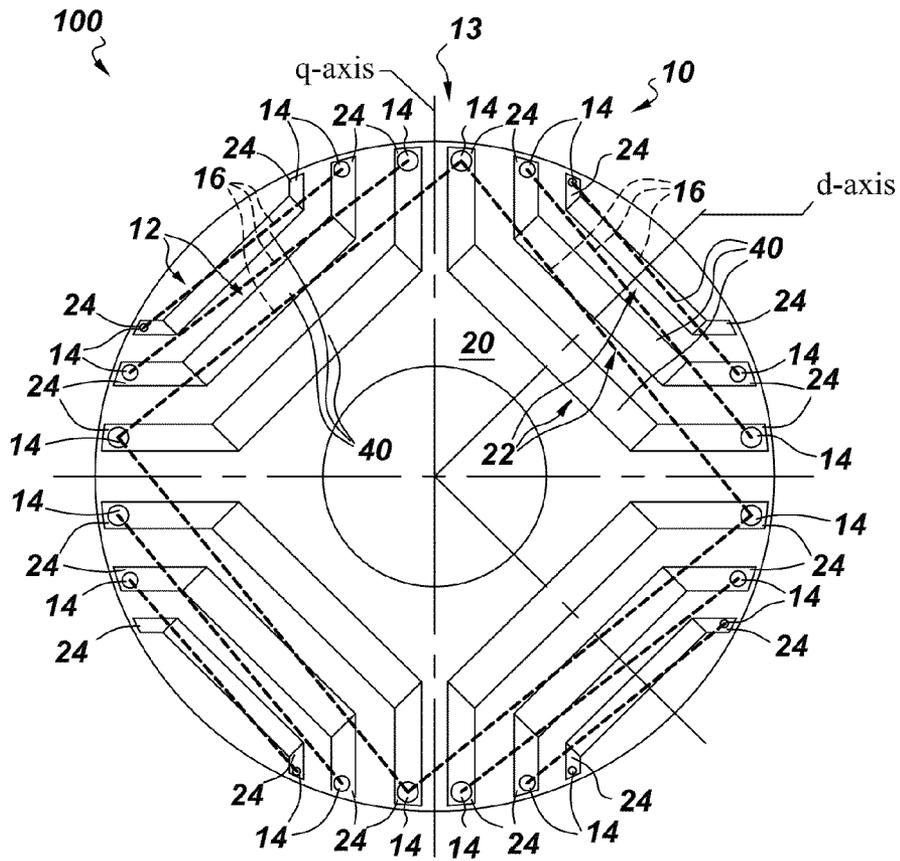


Fig. 15

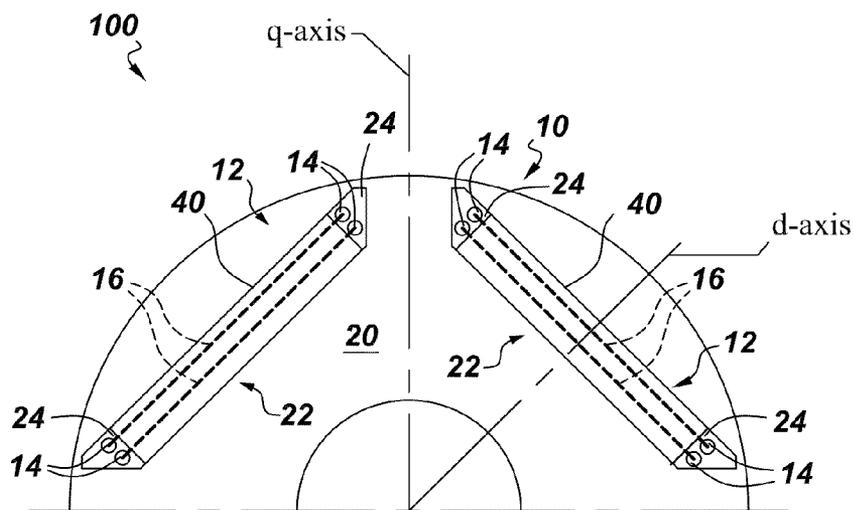
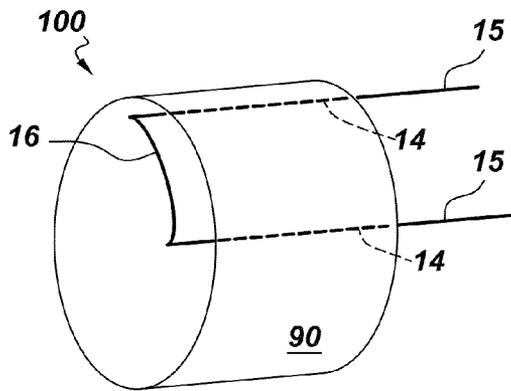
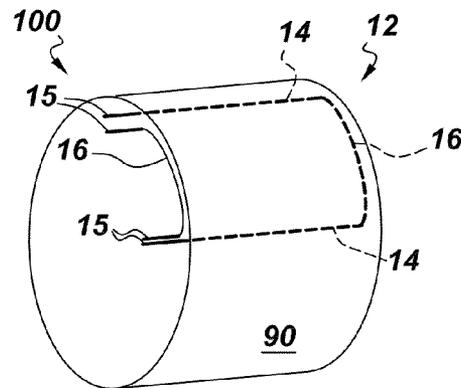


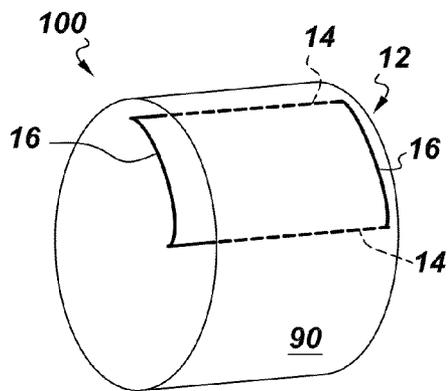
Fig. 16



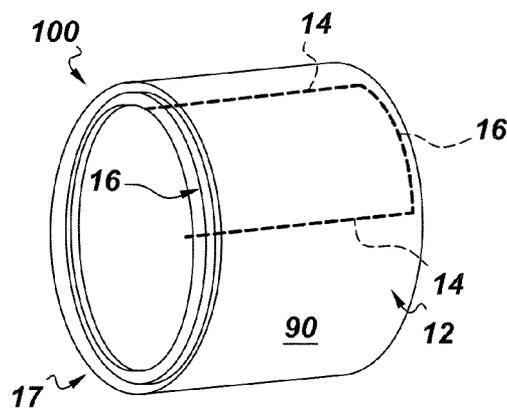
*Fig. 17A*



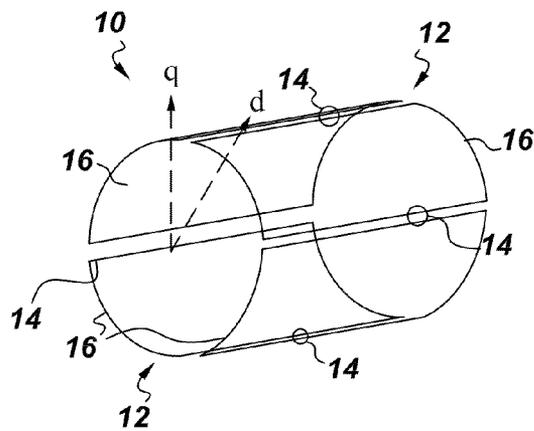
*Fig. 18*



*Fig. 17B*



*Fig. 19*



*Fig. 20*

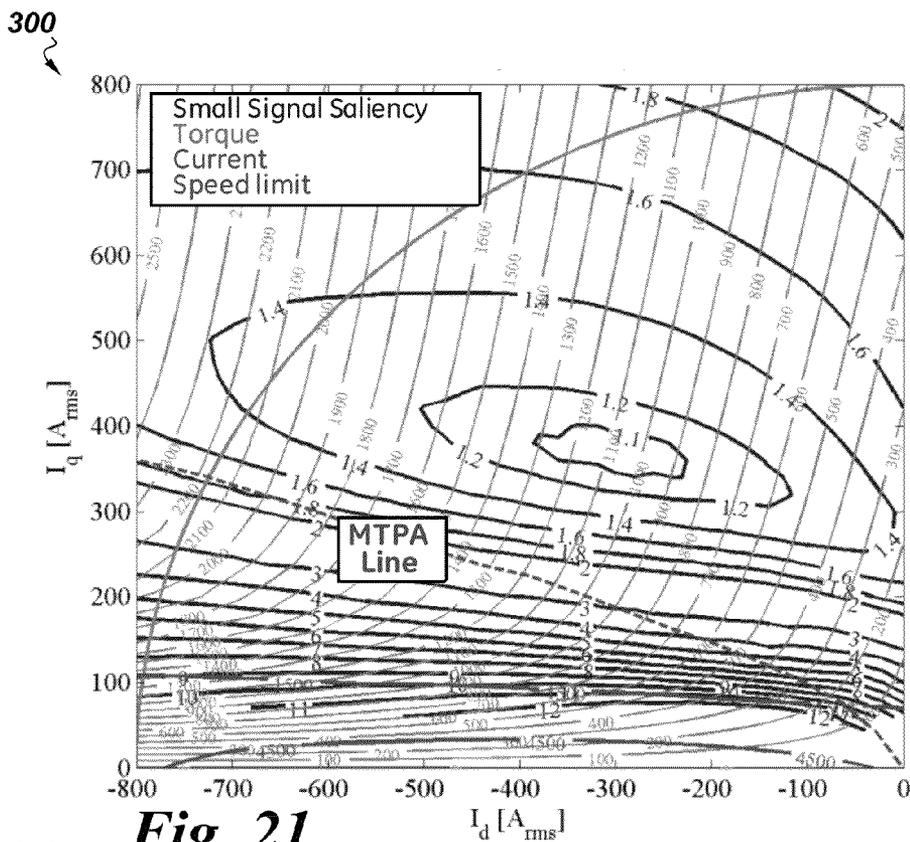


Fig. 21

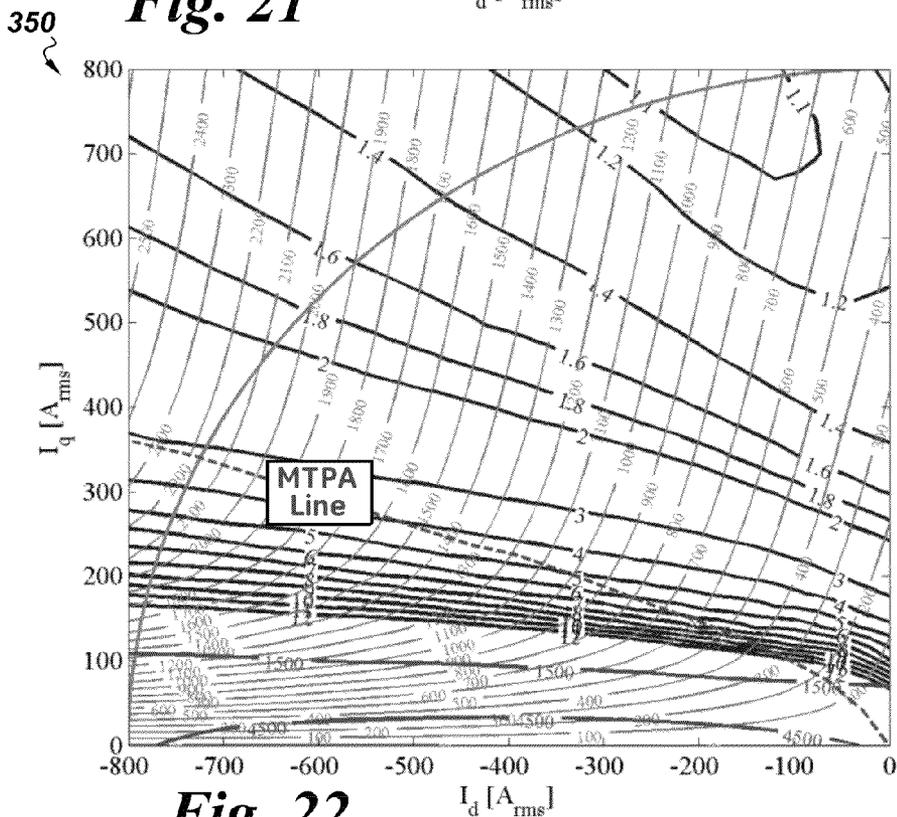


Fig. 22

400

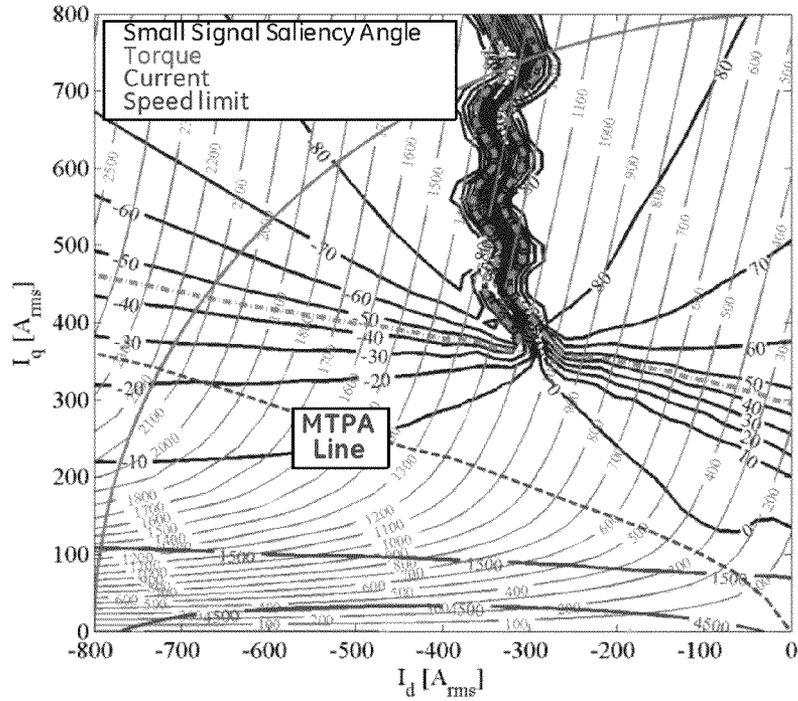


Fig. 23

450

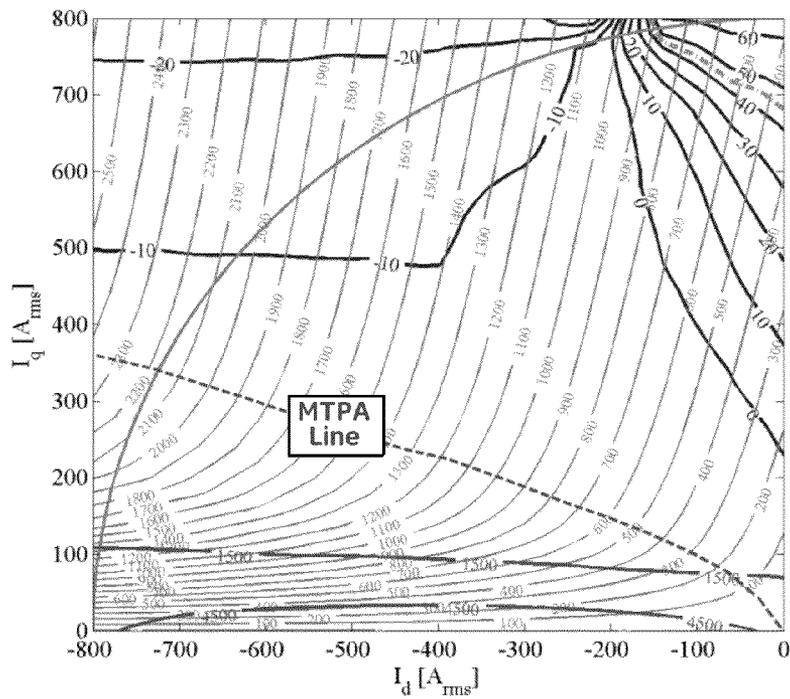
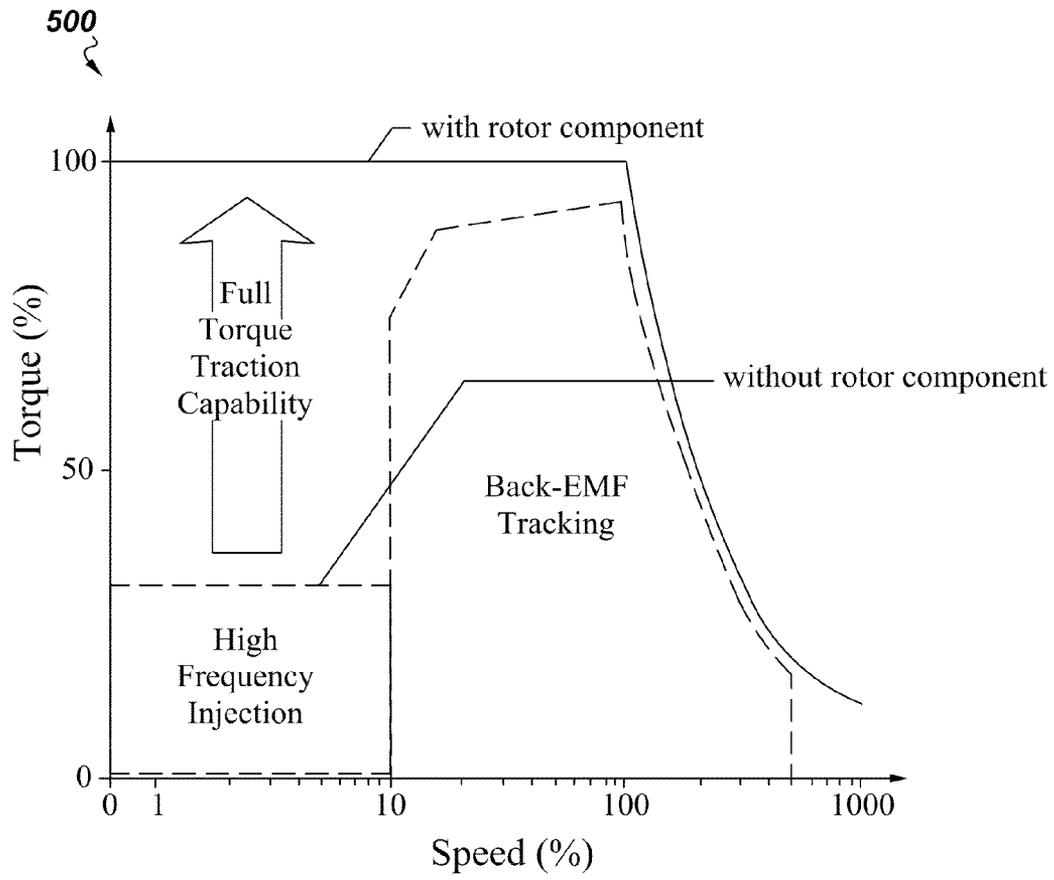


Fig. 24



**Fig. 25**

**SENSORLESS ELECTRIC MACHINE****BACKGROUND OF THE INVENTION**

The present invention relates generally to electric machines and more particularly to a sensorless electric machine, a component thereof, vehicles that employ the component and electric machine, and methods of making and operating the same.

With an electric machine, be it an interior permanent magnet (IPM) machine, permanent magnet (PM) assisted synchronous reluctance machine (SRM), or an SRM, position is a critical informational element for torque control at and near zero excitation frequency. Typically, an encoder, tachometer, or resolver is used with electric machines as the position sensor.

However, the position sensor (e.g., encoder) along with its cabling and interface electronics contributes a significant portion of the motor drive system cost and overall complexity and is often a major reliability concern. Since the advent of the high frequency injection method for zero frequency encoderless control, encoderless controls have seen great improvements but none have found success in recovering the full, or near full, torque capability of the machine. This is due to loss of small signal saliency at high-load levels for the machine.

Accordingly, there is an ongoing need for improvement of current electric machine technologies that address complexity, cost, efficiency, and/or performance.

**BRIEF DESCRIPTION**

The present invention overcomes at least some of the aforementioned drawbacks by providing improvements that allow electric machines, such as IPM motors to operate with full torque control without the need for any positions sensor (e.g., encoder). More specifically, the present invention is directed to a machine component and a machine that, when employing the component, is able to operate as a sensorless electric machine. A vehicle that uses one or more electric machines and methods of making and operating such an electric machine is/are also disclosed.

Therefore, in accordance with one aspect of the invention, a rotor component comprises a rotor circuit configured for use with one of an interior permanent magnet (IPM) machine and a synchronous reluctance machine (SRM), the rotor circuit comprising: at least one pole circuit, wherein the at least one pole circuit are made of a conductive, non-magnetic material.

In accordance with another aspect of the invention, an electric machine comprises a rotor core comprising magnetic steel; a stator configured with a plurality of stationary windings therein; a plurality of openings disposed within or on the rotor core; and a rotor circuit configured to introduce saliency based on an orientation of a portion of the rotor circuit in relationship to a pole location of the electric machine, said rotor circuit made of a conductive, non-magnetic material.

In accordance with another aspect of the invention, an electric machine comprises: a rotor core; a stator configured with a plurality of stationary windings therein; a plurality of openings disposed within the rotor core; and a rotor circuit structure comprising at least one pole circuit disposed in a predetermined location, wherein said predetermined location is in range that extends from about a q-axis to about a d-axis of the electric machine.

In accordance with another aspect of the invention, an electric machine comprising: a rotor core; a stator configured with a plurality of stationary windings therein; a plurality of

openings disposed within the rotor core; a rotatable shaft therethrough; and a rotor circuit structure comprising at least one loop or ring of a conductive, non-magnetic material, wherein said at least one loop or ring is substantially concentric about a d-axis of the electric machine.

In accordance with another aspect of the invention, an interior permanent magnet (IPM) machine comprises a means for converting electrical energy to rotational energy; and a means for providing increased magnetic saliency at high frequency excitation.

Various other features and advantages of the present invention will be made apparent from the following detailed description and the drawings.

**BRIEF DESCRIPTION OF THE DRAWINGS**

These and other features, aspects, and advantages of the present invention will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

FIG. 1 is a perspective view of a rotor circuit structure component according to an embodiment of the present invention.

FIG. 2 is a perspective view of rotor core of an electric machine incorporating a rotor circuit structure component according to an embodiment of the present invention.

FIG. 3A is a top view of a portion of a rotor lamination and rotor circuit structure component according to an embodiment of the present invention.

FIG. 3B is a schematic perspective diagram of the rotor circuit structure component in FIG. 3A according to an embodiment of the present invention.

FIG. 4A is a top view of a portion of a rotor lamination and rotor circuit structure component according to another embodiment of the present invention.

FIG. 4B is a schematic perspective diagram of the rotor circuit structure component in FIG. 4A according to an embodiment of the present invention.

FIG. 5A is a top view of a portion of a rotor lamination and rotor circuit structure component according to another embodiment of the present invention.

FIG. 5B is a schematic perspective diagram of the rotor circuit structure component in FIG. 5A according to an embodiment of the present invention.

FIG. 6A is a top view of a portion of a rotor lamination and rotor circuit structure component according to another embodiment of the present invention.

FIG. 6B is a schematic perspective diagram of the rotor circuit structure component in FIG. 6A according to an embodiment of the present invention.

FIG. 7A is a top view of a portion of a rotor lamination and rotor circuit structure component according to another embodiment of the present invention.

FIG. 7B is a schematic perspective diagram of the rotor circuit structure component in FIG. 7A according to an embodiment of the present invention.

FIG. 8A is a top view of a portion of a rotor lamination and rotor circuit structure component according to another embodiment of the present invention.

FIG. 8B is a schematic perspective diagram of the rotor circuit structure component in FIG. 8A according to an embodiment of the present invention.

FIG. 9A is a top view of a portion of a rotor lamination and rotor circuit structure component according to another embodiment of the present invention.

FIG. 9B is a schematic perspective diagram of the rotor circuit structure component in FIG. 9A according to an embodiment of the present invention.

FIGS. 10A, 10B, and 10C are schematic diagrams showing perspective views of a rotor circuit structure component according to embodiments of the present invention.

FIG. 11 is a schematic diagram of a top view of a portion of a rotor circuit structure component according to an embodiment of the present invention.

FIG. 12A is a schematic diagram of a top view of a portion of a rotor circuit structure component according to an embodiment of the present invention.

FIG. 12B is top view of a portion of a rotor lamination and the rotor circuit structure component of FIG. 12A according to another embodiment of the present invention.

FIG. 13 is a schematic diagram of a top view of a portion of a rotor circuit structure component according to an embodiment of the present invention.

FIG. 14A is a schematic diagram of a top view of a portion of a rotor circuit structure component according to an embodiment of the present invention.

FIG. 14B is top view of a portion of a rotor lamination and the rotor circuit structure component of FIG. 14A according to another embodiment of the present invention.

FIG. 15 is top view of a portion of a rotor lamination and the rotor circuit structure component according to another embodiment of the present invention.

FIG. 16 is top view of a portion of a rotor lamination and the rotor circuit structure component according to another embodiment of the present invention.

FIG. 17A is schematic diagram showing a perspective view of a partial installation of a portion of a rotor circuit structure component in a rotor portion of a machine according to an embodiment of the present invention.

FIG. 17B is schematic diagram showing a perspective view of a completed installation embodiment shown in FIG. 17A.

FIG. 18 is schematic diagram showing a perspective view of a completed installation of a portion of a rotor circuit structure component in a rotor portion of a machine according to another embodiment of the present invention.

FIG. 19 is schematic diagram showing a perspective view of a completed installation of a portion of a rotor circuit structure component in a rotor portion of a machine according to another embodiment of the present invention.

FIG. 20 is a schematic diagram showing a perspective view of a rotor circuit structure component according to another embodiment of the present invention.

FIG. 21 is a graph illustrating small signal saliency for electric machine of the related art.

FIG. 22 is a graph illustrating small signal saliency for an electric machine with a rotor circuit structure, according to an embodiment of the present invention.

FIG. 23 is a graph illustrating small signal saliency angle for electric machine of the related art.

FIG. 24 is a graph illustrating small signal saliency angle for an electric machine with a rotor circuit structure, according to an embodiment of the present invention.

FIG. 25 is a schematic graph comparing motor speed and torque for a related art machine (without a rotor structure) and a machine with a rotor circuit structure, according to an embodiment of the present invention.

#### DETAILED DESCRIPTION

Unless defined otherwise, technical and scientific terms used herein have the same meaning as is commonly understood by one of ordinary skill in the art with respect to the

presently disclosed subject matter. The terms “first”, “second”, and the like, as used herein do not denote any order, quantity, or importance, but rather are used to distinguish one element from another. The terms “a”, “an”, and “the” do not denote a limitation of quantity, but rather denote the presence of at least one of the referenced item, and the terms “front”, “back”, “bottom”, and/or “top”, unless otherwise noted, are used for convenience of description only, and are not limited to any one position or spatial orientation.

If ranges are disclosed, the endpoints of all ranges directed to the same component or property are inclusive and independently combinable (e.g., ranges of “up to about 25 wt. %,” is inclusive of the endpoints and all intermediate values of the ranges of “about 5 wt. % to about 25 wt. %,” etc.). The modified “about” used in connection with a quantity is inclusive of the stated value and has the meaning dictated by the context (e.g., includes the degree of error associated with measurement of the particular quantity). Accordingly, the value modified by the term “about” is not necessarily limited only to the precise value specified.

As used herein, the term “Pole Circuit” means one or more circuits that is affiliated with one pole of the electric machine. The one or more circuits may comprise one ring/loop, multiple rings/loops, one loop/ring of a cage, or one loop/ring of a cage with one or more inner rings/loops. The cage may be a shifted or non-shifted cage. Rings/loops may be shifted or non-shifted.

As used herein, the term “Shifted Cage” means one or more connected rings or loops wherein a rotor conductor (or if more than one rotor conductor are adjacent, then a midpoint between the plurality of adjacent rotor conductors) is not aligned with a q-axis of the machine, but instead is shifted by a distance from the q-axis. Contrastingly, a cage that is not shifted has a rotor conductor (or if more than one rotor conductor are adjacent, then a midpoint between the plurality of adjacent rotor conductors) that is aligned with the q-axis of the machine.

Aspects of the present invention have been shown to offer advantages over previous electric machine constructs. Aspects of the present invention provide design features for an electric machine (e.g., IPM motor) that enables full torque control without the use of any position sensor. An aspect of the present invention includes the use of a component, termed herein a special rotor structure that introduces magnetic saliency for high frequency excitation, wherein this high frequency excitation can be used for sensorless (e.g., encoderless) motor control. The rotor structure introduces electrical circuits (shorted circuit, closed circuit with passive or active elements) to specific orientation of the rotor so that it couples with the stator winding magnetically. The position of the rotor is measured by applying high frequency carrier voltage to the stator and by indirectly measuring the current of the rotor, by measuring the (reflected) high frequency carrier current response in the stator. If the rotor circuit is aligned in phase with the high frequency injection the impedance of the motor is reduced. This variation of impedance is used to track rotor position. As a result, small signal saliency up to necessary loading level is introduced and maintained without impact on electric machine performance, efficiency, and reliability.

Referring to FIG. 1 a rotor circuit or electrical component 10 incorporating aspects of the present invention is shown. The component 10 may comprise one or more rotor conductors (e.g., rotor bars 14) connected to one or more connection elements 16. As shown, the rotor bars 14 are substantially longitudinal in configuration. As will be discussed herein the component 10 and the rotor bars 14 and connection elements 16 are configured so as to substantially surround permanent

magnets **40** located in an electric machine **100**. In this manner two or more rotor bars **14** are connected to two or more connection elements **16** such that they define a loop or ring **12**. While the embodiment in FIG. **1** clearly shows a quantity of four rings **12** each ring **12** comprising two rotor bars **14** and two connection elements **16**, other quantities and configurations of elements of the component **10** are suitable without departing from the present invention. For example, the component **10** may comprise four rotor bars **14** and a plurality of connection elements **16** are either end of the component **10**, thereby defining a cage **13**. Similarly, in another embodiment, the component **10** may comprise a plurality of loops or rings **12**, wherein each ring **12** comprises four rotor bars **14** and two connection elements **16**. In still other embodiments, the ring(s) **12** and/or cage **13** may comprise virtually any quantity of conductors and/or connection elements.

The rotor bars **14** and connection elements **16** may be made of any suitable conductive, non-magnetic material, or combinations thereof. By example but not limitation, the rotor bars **14** and connection elements **16** may be castings made of aluminum, copper, alloys of copper or aluminum, or other suitable material or combination of materials.

It should be noted that although several of the embodiments discussed herein discuss the use of rotor bars, other conductive elements may be used in the component **10** without departing from the invention. For example, any suitable rotor conductor may be substituted in lieu of the rotor bars **14** that are discussed herein for the various embodiments. Other conductive elements for use in lieu of the rotor bars **14** and/or the connection elements **16** include, but are not limited to, one or more of multistranded bars, multi-stranded wire, litz wire, and combinations thereof.

Similarly, the rotor bar **14** has a cross-sectional shape that is suitable to address design factors including skin effect, cooling surface, structural strength, EM fitness, and the like. Suitable shapes for the cross-section of the rotor bar include a circle, square, rectangle, and the like.

The end perspective view of another embodiment of the component **10** located in rotor portion of a motor **100** is shown in FIG. **2**. The motor **100** includes a plurality of rotor core laminations **20** stacked so as to form a rotor core **90**. As shown, in the end view where a cover plate is omitted for illustrative purposes only so as to allow a first rotor core lamination **20** to be viewed. The rotor core lamination **20** includes a plurality of openings **22**. Permanent magnets **40** may be located within the plurality of openings **22**. For illustrative purposes only the permanent magnets **40** are shown disposed in only one set (e.g., at one pole) of openings **22**. The other three sets of openings **22** (i.e., four-pole machine) are shown without permanent magnets **40** therein. At the center of the rotor core lamination **20** is a shaft opening **94** configured to receive a rotatable shaft (not shown). As depicted, the component **10** is similar to the embodiment shown in FIG. **1** and comprises a quantity of four rings or loops **12**, each comprising two rotor bars **14** connected to two connection elements **16**. In this manner, two of the rotor bars **14** and the two connection elements **16** are interconnected so as to form a rotor ring or loop **12**. Four rotor rings or loops **12** are formed as part of the component **10** in this manner so as to match the quantity of poles (i.e., four) in the embodiment of the motor shown **100**.

Referring collectively to FIGS. **3A** and **3B**, a top view of a portion of a rotor lamination **20** portion of an electric machine **100** with a component **10** and a schematic diagram of a perspective view of the component **10** from FIG. **3A** are shown respectively. FIG. **3A** depicts a rotor lamination **20** of a single layer, four-pole IPM **100** having straight permanent

magnets **40** therein. FIG. **3B** depicts a rotor component **10** that may be termed a four-loop configuration. As shown and known in the art, the rotor lamination **20** includes a plurality of openings **22** that, depending on the particular embodiment, may have disposed therein one or more permanent magnets **40**. Once the permanent magnets **40** are disposed within the openings **22** there typically remains adjacent to either end of the permanent magnets **40** an opening, or remaining opening, **24**. For illustrative purposes only, the stator and/or stator windings are not shown that substantially surround the rotor component.

The plurality of rotor bars **14** are disposed in the plurality of openings **24** longitudinally through the stack of rotor laminations **20**. At or near either end of the stack of rotor laminations **20** are connection elements **16** that are connected to both ends of the rotor bars **14**. In this manner, the component **10** embodiment in FIG. **3B** has four rotor loops **12** each constructed of two rotor bars **14** and two connection elements **16**, thereby matching the quantity of poles (i.e., four) for the particular machine **100**.

Referring collectively to FIGS. **4A** and **4B**, a top view of a portion of a rotor lamination **20** portion of an electric machine **100** with a component **10** and a schematic diagram of a perspective view of the component **10** from FIG. **4A** are shown respectively. FIG. **4A** depicts a rotor lamination **20** of a single layer, four-pole IPM **100** having straight permanent magnets **40** therein. FIG. **4B** depicts a rotor component **10** that may be termed a four-loop, shifted-ring configuration. As shown and known in the art, the rotor lamination **20** includes a plurality of openings **22** that, depending on the particular embodiment, may have disposed therein one or more permanent magnets **40**. Once the permanent magnets **40** are disposed within the openings **22** there typically remains adjacent to either end of the permanent magnets **40** an opening, or remaining opening, **24**. For illustrative purposes only, the stator and/or stator windings are not shown that substantially surround the rotor component.

The plurality of rotor bars **14** are disposed in some of the plurality of openings **24** longitudinally through the stack of rotor laminations **20**. In this embodiment two adjacent rotor bars **14** are co-located in a single opening **24** while the opening **24** at the other end of the magnet **40** is left unfilled. At or near either end of the stack of rotor laminations **20** are connection elements **16** that are connected to both ends of the rotor bars **14**. In this manner, the component **10** embodiment in FIG. **4B** has four rotor loops **12** each constructed of two rotor bars **14** and two connection elements **16**, thereby matching the quantity of poles (i.e., four) for the particular machine **100**. By co-locating the two rotor bars **14** from adjacent poles, the four loops **12** are effectively connected to each other, thereby forming shifted rings **13**.

Referring collectively to FIGS. **5A** and **5B**, a top view of a portion of a rotor lamination **20** portion of an electric machine **100** with a component **10** and a schematic diagram of a perspective view of the component **10** from FIG. **5A** are shown respectively. FIG. **5A** depicts a rotor lamination **20** of a single layer, four-pole IPM **100** having straight permanent magnets **40** therein. FIG. **5B** depicts a rotor component **10** that may be termed a four-loop, shifted-cage configuration, similar to the embodiment shown in FIGS. **4A** and **4B**. As shown and known in the art, the rotor lamination **20** includes a plurality of openings **22** that, depending on the particular embodiment, may have disposed therein one or more permanent magnets **40**. Once the permanent magnets **40** are disposed within the openings **22** there typically remains adjacent to either end of the permanent magnets **40** an opening, or remaining opening, **24**. For illustrative purposes only, the

stator and/or stator windings are not shown that substantially surround the rotor component.

The plurality of rotor bars **14** are disposed in some of the plurality of openings **24** longitudinally through the stack of rotor laminations **20**. In this embodiment instead of co-locating two adjacent rotor bars **14** in a single opening **24** (as done in FIG. **4A**), the two adjacent rotor bars **14** are combined into a single rotor bar **14**. Again, the opening **24** at the other end of the magnet **40** is left unfilled. At or near either end of the stack of rotor laminations **20** are connection elements **16** that are connected to both ends of the rotor bars **14**. In this manner, the component **10** embodiment in FIG. **5B** has four rotor loops **12** each constructed of two rotor bars **14** and two connection elements **16**, thereby matching the quantity of poles (i.e., four) for the particular machine **100**. However, the quantity of total rotor bars **14** is less due to the effective sharing of rotor bars **14** from the adjacent loops **12** (and poles). The component **10** has eight connection elements **16** but four rotor bars **14** for use in a four pole machine **100**. By cross connecting adjacent loops **12** with the connection elements **16** from adjacent poles, the four loops **12** are effectively connected to each other, thereby forming a cage, or shifted cage **13**.

Referring collectively to FIGS. **6A** and **6B**, a top view of a portion of a rotor lamination **20** portion of an electric machine **100** with a component **10** and a schematic diagram of a perspective view of the component **10** from FIG. **6A** are shown respectively. FIG. **6A** depicts a rotor lamination **20** of a spoke-type, four-pole IPM **100** having straight permanent magnets **40** therein. FIG. **6B** depicts a rotor component **10** that may be termed a four-loop configuration. As shown and known in the art, the rotor lamination **20** includes a plurality of openings **22** that, depending on the particular embodiment, may have disposed therein one or more permanent magnets **40**. Once the permanent magnets **40** are disposed within the openings **22** there typically remains adjacent to either end of the permanent magnets **40** an opening, or remaining opening, **24**. For illustrative purposes only, the stator and/or stator windings are not shown that substantially surround the rotor component.

The plurality of rotor bars **14** are disposed in the plurality of outboard openings **24** longitudinally through the stack of rotor laminations **20**. At or near either end of the stack of rotor laminations **20** are connection elements **16** that are connected to both ends of the rotor bars **14**. In this manner, the component **10** embodiment in FIG. **6B** has four rotor loops **12** each constructed of two rotor bars **14** and two connection elements **16**, thereby matching the quantity of poles (i.e., four) for the particular machine **100**.

Referring collectively to FIGS. **7A** and **7B**, a top view of a portion of a rotor lamination **20** portion of an electric machine **100** with a component **10** and a schematic diagram of a perspective view of the component **10** from FIG. **7A** are shown respectively. FIG. **7A** depicts a rotor lamination **20** of a spoke-type, four-pole IPM **100** having straight permanent magnets **40** therein. FIG. **7B** depicts a rotor component **10** that may be termed a four-loop, rotor cage configuration, similar in aspects to the embodiment shown in FIGS. **6A** and **6B**. As shown and known in the art, the rotor lamination **20** includes a plurality of openings **22** that, depending on the particular embodiment, may have disposed therein one or more permanent magnets **40**. Once the permanent magnets **40** are disposed within the openings **22** there typically remains adjacent to either end of the permanent magnets **40** an opening, or remaining opening, **24**. For illustrative purposes only, the stator and/or stator windings are not shown that substantially surround the rotor component.

The plurality of rotor bars **14** are disposed in the outboard plurality of openings **24** longitudinally through the stack of rotor laminations **20**. In this embodiment instead of co-locating two adjacent rotor bars **14** in a single opening **24** (as done in FIG. **6A**), the two adjacent rotor bars **14** are combined into a single rotor bar **14**. At or near either end of the stack of rotor laminations **20** are connection elements **16** that are connected to both ends of the rotor bars **14**. In this manner, the component **10** embodiment in FIG. **7B** has four rotor loops **12** each constructed of two rotor bars **14** and two connection elements **16**, thereby matching the quantity of poles (i.e., four) for the particular machine **100**. However, the quantity of total rotor bars **14** is less due to the effective sharing of rotor bars **14** from the adjacent loops **12** (and poles). The component **10** thus comprises eight connection elements **16** but four rotor bars **14** total for use in a four pole machine **100**. By cross connecting adjacent loops **12** with the connection elements **16** from adjacent poles, the four loops **12** are effectively connected to each other, thereby forming a cage **13**.

Referring collectively to FIGS. **8A** and **8B**, a top view of a portion of a rotor lamination **20** portion of an electric machine **100** with a component **10** and a schematic diagram of a perspective view of the component **10** from FIG. **8A** are shown respectively. FIG. **8A** depicts a rotor lamination **20** of a multi-layer, four-pole IPM **100** having straight permanent magnets **40** therein. FIG. **8B** depicts a rotor component **10** that may be termed a four-loop configuration. As shown and known in the art, the rotor lamination **20** includes a plurality of openings **22** that, depending on the particular embodiment, may have disposed therein one or more permanent magnets **40**. Once the permanent magnets **40** are disposed within the openings **22** there typically remains adjacent to either end of the permanent magnets **40** an opening, or remaining opening, **24**. For illustrative purposes only, the stator and/or stator windings are not shown that substantially surround the rotor component. As with multi-layer IPM, there is typically a plurality of rows of openings **22** and permanent magnets **40** therein located for each pole.

The plurality of rotor bars **14** are disposed in the plurality of openings **24** longitudinally through the stack of rotor laminations **20**. At or near either end of the stack of rotor laminations **20** are connection elements **16** that are connected to both ends of the rotor bars **14**. In this manner, the component **10** embodiment in FIG. **8B** has four rotor loops **12** each constructed of two rotor bars **14** and two connection elements **16**, thereby matching the quantity of poles (i.e., four) for the particular machine **100**. In this particular embodiment, the rotor bars **14** are located in the furthest inboard openings **24** of the multi-layer rotor lamination **20**. It should be apparent, that the rotor bars could be located in other openings **24** of the lamination **20**.

Referring collectively to FIGS. **9A** and **9B**, a top view of (an entire) portion of a rotor lamination **20** portion of an electric machine **100** with a component **10** and a schematic diagram of a perspective view of the component **10** from FIG. **9A** are shown respectively. FIG. **9A** depicts a rotor lamination **20** of a multi-layer, four-pole IPM **100** having straight permanent magnets **40** therein. FIG. **9B** depicts a rotor component **10** that may be termed a four-loop, cage or shifted-cage configuration. As shown and known in the art, the rotor lamination **20** includes a plurality of openings **22** that, depending on the particular embodiment, may have disposed therein one or more permanent magnets **40**. Once the permanent magnets **40** are disposed within the openings **22** there typically remains adjacent to either end of the permanent magnets **40** an opening, or remaining opening, **24**. For illustrative purposes only, the stator and/or stator windings are not shown

that substantially surround the rotor component. As with multi-layer IPM, there is typically a plurality of rows of openings **22** and permanent magnets **40** therein located for each pole.

The plurality of rotor bars **14** are disposed in the plurality of openings **24** longitudinally through the stack of rotor laminations **20**. In this configuration only a single rotor bar **14** is placed in an opening **24** in each pole (See FIG. 9A). At or near either end of the stack of rotor laminations **20** are connection elements **16** that are connected to both ends of the rotor bars **14**. The connection element **16** connects a rotor bar **14** from a first pole to the rotor bar **14** of an adjacent pole, thereby shifting the element **10**. In this manner, the component **10** embodiment in FIG. 9B has four rotor loops **12** each constructed of two rotor bars **14** and two connection elements **16**, thereby matching the quantity of poles (i.e., four) for the particular machine **100**. However, due to the shifted-cage configuration of the embodiment, only four rotor bars **14** total and eight connection elements **16** are required for a four-pole machine **100** such as that depicted. In this particular embodiment, the rotor bars **14** are located in the furthest inboard openings **24** of the multi-layer rotor lamination **20**. It should be apparent, that the rotor bars could be located in other openings **24** of the lamination **20**.

Referring collectively to FIGS. 10A, 10B, and 10C, schematic diagrams of perspective views of components **10** according to aspects of the present invention are shown. The figures are provided to show various schematic embodiments to show the general positional relationship between various elements of the component **10** and a d-axis and q-axis of a machine (not) that may employ the component **10**. The d-axis (direct axis) and the q-axis (quadrature axis) are denoted by arrows labeled "d" and "q", respectively. As shown in FIG. 10A, a component **10** includes four rotor loops or rings **12**. Each ring **12** comprises two rotor bars **14** connected at each end to a connector element **16**. Rotor bars **14** are effectively shared by adjacent rings **12** so that all four rings **12** are connected. There are a total of four rotor bars **14** for the element **10**. Because the rotor bars **14** are effectively shared by adjacent poles or the component **10**, only four rotor bars **14** are needed by the component **10** for use with a four-pole machine (not shown). In this manner, the four loops **12**, being interconnected, effectively define a cage **13**. As shown, the approximate midpoint of the loop **12** aligns with the d-axis. In other words, a loop **12** is substantially concentric with the d-axis. Similarly, the q-axis may substantially align with a rotor bar **14**.

As shown in FIG. 10B, the four rings **12** are not interconnected as in the embodiment shown in FIG. 10A. Each ring **12** comprises two rotor bars **14** and two connector elements **16**. As shown, and as with the embodiment in FIG. 10A, the approximate midpoint of the loop **12** aligns with the d-axis. In other words, a loop **12** is substantially concentric with the d-axis. Similarly, the q-axis may substantially align with a conceptual line or axis between two adjacent rotor bars **14**.

Referring to the embodiment shown in FIG. 10C, the element **10** comprises four rotor loops or rings **12**. Each ring **12** comprises two rotor bars **14** connected at each end to a connector element **16**. Rotor bars **14** are effectively shared by adjacent rings **12** so that all four rings **12** are connected, effectively defining a shifted cage **13** configuration. Thus, there are a total of four rotor bars **14** for the element **10**. As shown, and as with the embodiments in FIGS. 10A and 10B, the approximate midpoint of the loop **12** aligns with the d-axis. In other words, a loop **12** is substantially concentric with the d-axis. However, in the embodiment shown in FIG.

10C, the rotor bar **14** does not align with the q-axis but is shifted by a certain angle (or distance) from the q-axis.

As shown in FIGS. 10A-10C, each embodiment is configured such that the d-axis aligns about with the midpoint of connector element **16**. That is a loop **12** or plurality of inner loops may be substantially concentric with the d-axis. However, depending on the embodiment the rotor bar **14** or an equidistant axis between adjacent rotor bars **14** may align with the q-axis as shown in FIGS. 10A and 10B, respectively. Contrastingly, as shown for example in FIG. 10C, the rotor bar **14** or an equidistant axis between adjacent rotor bars **14** may be offset, or shifted, from being aligned with the q-axis. The embodiments shown are configured for use in a four-pole machine **100**. It should be apparent to one skilled in the art that other configurations of elements **10** are allowed without departing from aspects of the present invention. For example, an element **10** configured for use in an eight-pole machine **100** would contrastingly have at least eight rotor bars **14**. In embodiments of the present invention, the quantity of rotor bars **14** would equal the quantity of poles of the machine **100** (see e.g., FIGS. 10A and 10C). Contrastingly, in other embodiments, such as the element **10** shown in FIG. 10B, the quantity of rotor bars **14** (e.g., eight) may be double the quantity of poles (e.g., four) of the machine **100**. Clearly, other configurations of elements **10** that have differing quantities of rotor bars **14** in view of quantity of poles of the machine **100** in which the element **10** is configured for are available under aspects of the present invention without departing from the intent of the invention.

Referring to FIGS. 11 and 12A, schematic diagrams of top views of a portion of a rotor structure component **10** according to embodiments of the present invention are shown. (These schematic views are such that effectively it is as if the component **10** were opened and rolled out flat, in a planar fashion, on the plane of the page). The component **10** comprises a plurality of rotor bars **14** connected to a plurality of connection elements **16**. The component **10** in FIG. 11 comprises a single ring **12** per pole of the machine **100** (not shown). The two adjacent rotor bars **14** align with the q-axis and the approximate midpoint of the ring **12** aligns with the d-axis. That is the ring **12** on the right side in the FIG. 11 is substantially concentric with the d-axis. Alternatively, the component **10** of FIG. 12A comprise multiple rings **12** per pole of the machine **100** (not shown). Multiple rings **12** can further assist in further increasing saliency. There are three rings **12** per pole on the component **10** shown. The outermost two adjacent rotor bars **14** of the rings **12** align with the q-axis and the approximate midpoints of the multiple rings **12** align with the d-axis. That is the rings **12** on the right side in the FIG. 12A are substantially concentric with the d-axis. It should be apparent that although three rings **12** are depicted, other configurations and quantities are allowable without departing from aspects of the present invention.

Referring to FIG. 12B, a top view of a portion of a rotor lamination **20** portion of an electric machine **100** with a component **10** and a schematic diagram of a perspective view of the component **10** from FIG. 12A is shown. FIG. 12B depicts a rotor lamination **20** of a multi-layer, four-pole IPM **100** having straight permanent magnets **40** therein. Some attributes of the embodiment shown are similar to the embodiment shown in FIG. 8A. As shown and known in the art, the rotor lamination **20** includes a plurality of openings **22** that, depending on the particular embodiment, may have disposed therein one or more permanent magnets **40**. Once the permanent magnets **40** are disposed within the openings **22** there typically remains adjacent to either end of the permanent magnets **40** an opening, or remaining opening, **24**. For

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illustrative purposes only, the stator and/or stator windings are not shown that substantially surround the rotor component. As with multi-layer IPM, there is typically a plurality of rows of openings 22 and permanent magnets 40 therein located for each pole.

The plurality of rotor bars 14 are disposed in the plurality of openings 24 longitudinally through the stack of rotor laminations 20. At or near either end of the stack of rotor laminations 20 are connection elements 16 that are connected to both ends of the rotor bars 14. In this manner, the component 10 embodiment in FIG. 12B has four rotor loops 12 each constructed of two rotor bars 14 and two connection elements 16, thereby matching the quantity of poles (i.e., four) for the particular machine 100. However, there are two inner rings or loops 12 for each ring or loop 12 (See FIG. 12A). As shown, the rotor bars 14 for each of the two inner rings or loops 12 also are inserted into the openings 24 adjacent to magnets 40.

Referring to FIGS. 13 and 14A, schematic diagrams of top views of a portion of a rotor structure component 10 according to embodiments of the present invention are shown. (These schematic views are such that effectively it is as if the component 10 were opened and rolled out flat, in a planar fashion, on the plane of the page). The component 10 comprises a plurality of rotor bars 14 connected to a plurality of connection elements 16. The rotor bars 14 are shared by adjacent loops or rings 12. As such the rings 12 collectively form a cage 13. The component 10 in FIG. 13 comprises a cage 13 with a single loop 12 per pole of the machine 100 (not shown). The single, shared rotor bar 14 aligns with the q-axis and the approximate midpoint of the loops 12 of the cage 13 aligns with the d-axis. That is the ring 12 of the cage 13 on the right side in the FIG. 13 is substantially concentric with the d-axis. Alternatively, the component 10 of FIG. 14A comprise a cage 13 also having multiple inner rings 12 per pole of the machine 100 (not shown). The additional multiple rings 12 can further assist in further increasing saliency. There are two inner rings 12 per pole on the component 10 in addition to the cage 13. The shared rotor bar 14 of the cage 13 aligns with the q-axis and the approximate midpoints of the multiple inner rings 12 and the cage 13 align with the d-axis. That is the rings 12 and the cage 13 on the right side in the FIG. 14A is substantially concentric with the d-axis. It should be apparent that although two rings 12 are depicted in addition to the cage 13, other configurations and quantities are allowable without departing from aspects of the present invention.

Referring to FIG. 14B, a top view of a portion of a rotor lamination 20 portion of an electric machine 100 with a component 10 and a schematic diagram of a perspective view of the component 10 from FIG. 14A is shown. FIG. 14B depicts a rotor lamination 20 of a combination multi-layer/spoke-type, four-pole IPM 100 having straight permanent magnets 40 therein. Some attributes of the embodiment shown are similar to the embodiments shown in both FIG. 7A and FIG. 8A. As shown and known in the art, the rotor lamination 20 includes a plurality of openings 22 that, depending on the particular embodiment, may have disposed therein one or more permanent magnets 40. Once the permanent magnets 40 are disposed within the openings 22 there typically remains adjacent to either end of the permanent magnets 40 an opening, or remaining opening, 24. For illustrative purposes only, the stator and/or stator windings are not shown that substantially surround the rotor component. As with multi-layer IPM, there is typically a plurality of rows of openings 22 and permanent magnets 40 therein located for each pole. As shown, the spoke-type aspect of the IPM 100 also includes magnets 40 that are radially disposed in a plurality of openings 22. Once the permanent magnets 40 are

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disposed within the openings 22 there typically remains adjacent to either end of the permanent magnets 40 an opening 24.

The plurality of rotor bars 14 are disposed in the plurality of openings 24 longitudinally through the stack of rotor laminations 20. At or near either end of the stack of rotor laminations 20 are connection elements 16 that are connected to both ends of the rotor bars 14. As shown in FIG. 14A, the outer rings 12 share common rotor bars 14, thereby defining a cage 13. In this manner, the component 10 embodiment in FIG. 14B has four rotor loops 12 each constructed of two rotor bars 14 and two connection elements 16, thereby matching the quantity of poles (i.e., four) for the particular machine 100. The four rotor loops 12 sharing common rotor bars 14 thereby defines a cage 13. Thus, the cage 13 may be formed of four rotor bars 14 and eight total connector elements 16. However, there are also two inner rings or loops 12 for each outer ring or loop 12 (See FIG. 14A). As shown, the rotor bars 14 for each of the two inner rings or loops 12 also are inserted into the openings 24 adjacent to magnets 40. The rotor bars 14 for the cage 13 may be inserted in the openings 24 adjacent to the spoke-type magnets 40. The rotor bars 14 for the two inner loops or rings 12 may be inserted in the openings 24 adjacent to the multi-layer type magnets 40.

Referring to FIG. 15, a top view of (an entire) portion of a rotor lamination 20 portion of an electric machine 100 with a component 10 is shown. FIG. 15 depicts a rotor lamination 20 of a multi-layer, four-pole IPM 100 having straight permanent magnets 40 therein. This embodiment is similar in some aspects to the embodiments illustrated in FIGS. 9A and 9B and the FIGS. 14A and 14B. The rotor component 10 may be termed a shifted-cage with inner rings or loops configuration. As shown and known in the art, the rotor lamination 20 includes a plurality of openings 22 that, depending on the particular embodiment, may have disposed therein one or more permanent magnets 40. Once the permanent magnets 40 are disposed within the openings 22 there typically remains adjacent to either end of the permanent magnets 40 an opening, or remaining opening, 24. For illustrative purposes only, the stator and/or stator windings are not shown that substantially surround the rotor component. As with multi-layer IPM, there is typically a plurality of rows of openings 22 and permanent magnets 40 therein located for each pole.

The plurality of rotor bars 14 are disposed in the plurality of openings 24 longitudinally through the stack of rotor laminations 20. In this configuration only a single rotor bar 14 is placed in an opening 24 in each pole (See FIG. 9A). At or near either end of the stack of rotor laminations 20 are connection elements 16 that are connected to both ends of the rotor bars 14. The connection element 16 connects a rotor bar 14 from a first pole to the rotor bar 14 of an adjacent pole, thereby shifting the element 16 creating a shifted cage 13 configuration. In this manner, the component 10 embodiment has four rotor loops 12 each constructed of two rotor bars 14 and two connection elements 16, thereby matching the quantity of poles (i.e., four) for the particular machine 100. However, due to the shifted-cage configuration of the embodiment, only four rotor bars 14 total and eight connection elements 16 are required for a four-pole machine 100 such as that depicted. In this particular embodiment, the rotor bars 14 are located in the furthest inboard openings 24 of the multi-layer rotor lamination 20. It should be apparent, that the rotor bars could be located in other openings 24 of the lamination 20. In addition, there are two additional inner loops 12 for each pole that are shifted in their configuration as well.

Referring to FIG. 16, a top view of a portion of a rotor lamination 20 portion of an electric machine 100 with a component 10 is shown. FIG. 16 depicts a rotor lamination 20

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of a single layer, four-pole IPM **100** having straight permanent magnets **40** therein. (The embodiment is similar in aspects to the embodiment shown in FIGS. **3A** and **3B**). As shown and known in the art, the rotor lamination **20** includes a plurality of stator windings (not shown) and inboard of the stator windings are disposed one or more permanent magnets **40** located in one or more openings **22** in the rotor lamination **20**. Once the permanent magnets **40** are disposed within the openings **22** there typically remains adjacent to either end of the permanent magnets **40** an opening **24**.

The plurality of rotor bars **14** are disposed in the plurality of openings **24** longitudinally through the stack of rotor laminations **20**. At or near either end of the stack of rotor laminations **20** are connection elements **16** that are connected to both ends of the rotor bars **14**. In this embodiment, one or more ring **12** (i.e., rotor bars **14** and connection elements **16**) is split into two or more rings **12**. As shown, there are two rotor bars **14** placed in the openings **24**, and there are two connection elements **16** connecting the two rotor bars **14**. In this manner, the component **10** embodiment in FIG. **16** has four rotor loops **12** where each loop **12** is constructed of four rotor bars **14** and four connection elements **16** for the particular machine **100**. By splitting the loops into multiple loops (term “split rotor bar” configuration) fault tolerance is provided. As long as at least one loop in the plurality of loops remains functional, the ring **12** will be able to introduce the desired ring saliency. It should be apparent that under aspects of the present invention that various configurations of splitting, via design, a connection element **16**, rotor bar **14**, loop **12**, and/or cage **13** into two or more elements other than that shown is possible. For example, the elements may be in other quantities than just two (as depicted in FIG. **16**).

Referring collectively to FIGS. **17A**, **17B**, **17**, and **18**, schematic diagrams of perspective views of various embodiments showing the installation of a portion of a component **10** in a machine **100** in accordance with aspects of the present invention. While FIG. **17A** shows a partial installation of an element, while FIG. **17B** shows the completed installation of the element from FIG. **17A**. A U-shaped element, which may be pre-formed (e.g., bent), is made of a conductive, non-magnetic material comprising two rotor bars **12** connected via a connection element **16**. The U-shaped element may be inserted into two openings (e.g., **24**) in the rotor **90** of the machine **100** (not fully shown). As shown, each of the rotor bars **14** has extensions **15** that extend beyond the length of the rotor core **90** of the machine **100**. The extensions **15** may then be bent and connected together to form a second connection element **16**, thereby forming a completed ring **12**, as shown in FIG. **17B**. The extensions **15** may be connected by any known method including, but not limited to, brazing, welding, mechanically fastening, and the like.

Referring to the embodiment shown in FIG. **18**, a U-shaped element (similar to the embodiment discussed in FIG. **17A**) comprising element, which may be pre-formed (e.g., bent), is made of a conductive, non-magnetic material comprising two rotor bars **12** connected via a connection element **16**. The U-shaped element may be inserted into two openings (e.g., **24**) in the rotor **90** of the machine **100** (not entirely shown). As shown, each of the rotor bars **14** has extensions **15** that extend beyond the length of the rotor **90** of the machine **100**. In a typical embodiment, the extensions **15** of the embodiment in FIG. **18** do not need to be as long as the extensions **15** of the embodiment in FIG. **17A**. A small U-shaped end piece **18**, made of a conductive material, having extensions **15** may be placed so that the respective extensions **15** of the end piece **18** and the U-shaped element are adjacent to each other. The extensions **15** may be connected by suitable means (e.g.,

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brazing, welding, mechanical fastening, etc.) thereby creating a loop **12**. It should be noted that the end piece need not be U-shaped as discussed above. For example, in another embodiment, a straight element like connection element **16** without extensions **15** may be used in lieu of the U-shaped end piece **18**, wherein the connection element **16** is attached to the U-shaped element and connected thereto.

Referring to the embodiment shown in FIG. **19**, a U-shaped element (similar to the embodiment discussed in FIG. **18**) comprising element, which may be pre-formed (e.g., bent), is made of a conductive, non-magnetic material comprising two rotor bars **12** connected via a connection element **16**. The U-shaped element may be inserted into two openings (e.g., **24**) in the rotor **90** of the machine **100**. As shown, each of the rotor bars **14** has extensions **15** that extend beyond the length of the rotor **90** of the machine **100**. In a typical embodiment, the extensions **15** of the embodiment in FIG. **19** do not need to be as long as the extensions **15** of the embodiment in FIG. **17A**. A full-ring connector **17**, made of conductive material, may be placed so that the extensions **15** of the U-shaped element are adjacent to and/or extending through the connector **17**. The extensions **15** and/or rotor bars **14** may be connected to the connector **17** by suitable means (e.g., brazing, welding, mechanical fastening, etc.) thereby creating a loop **12**.

Referring to FIG. **20**, a schematic diagram of a perspective view of a component **10** according to an aspect of the present invention is shown. The d-axis (direct axis) and the q-axis (quadrature axis) are denoted by arrows labeled “d” and “q”, respectively. As shown, the component **10** includes four rotor loops or rings **12**. Each ring **12** comprises two rotor bars **14** connected at one end to a connector element **16**. The other ends of the rotor bars **14** are connected to a single full ring connector **17**. In this manner, all rings **12** are effectively connected to the full ring connector **17**, thereby defining a cage **13**. There are a total of eight rotor bars **14** for the element **10**. In this manner, the four loops **12**, being interconnected, effectively define a cage **13**. As shown, the approximate midpoint of a loop **12** aligns with the d-axis. In other words, a loop **12** is substantially concentric with the d-axis. Similarly, the q-axis substantially aligns with a midpoint between two adjacent rotor bars **14**.

While various embodiments discussed herein have general disclosed magnets **40** and openings **22** of specific sizes and configurations, it should be apparent that different quantities, shapes, and configurations that those illustrated may be used without departing from aspects of the present invention. For example, the openings **22** and/or magnets **40** may be other shapes other than straight including, for example, curved, trapezoidal, round, and the like, and combinations thereof.

While various embodiments discussed herein have general disclosed rotor conductors (e.g., rotor bars **14**) disposed in openings **24** adjacent to magnets **40** in the rotor lamination **20**, it should be apparent that under aspects of the present invention that the rotor conductors, in certain embodiments, are disposed in openings and/or voids (e.g., grooves, channels, gaps, etc.) on the outer portion **90** of the rotor. In other words, in embodiments the rotor conductors may be placed in a location such that, at least initially, is not fully surrounded by rotor lamination material.

Finite-element analysis based modeling was conducting on various models of machines, both for electric machines not having any rotor circuit structure (i.e., related art) and for electric machines using embodiments of the rotor circuit structures of the present invention. Some results of the modeling are illustrated in FIGS. **21-24** herein.

Small signal saliency and small signal saliency angle is key information used for sensorless control, under aspects of the present invention, and it is defined using small signal impedance. Small signal impedance is defined for a small high frequency variation of current ( $\Delta i_d, \Delta i_q$ ) from the operating point current vector ( $i_d, i_q$ ). Small signal impedance varies depending on the orientation of the high frequency current variation ( $\Delta i_d, \Delta i_q$ ). Small signal saliency at a given operating point ( $\Delta i_d, \Delta i_q$ ) is the ratio of the maximum small signal impedance to the minimum small signal impedance over a full range of orientation of the high frequency current variation. Small signal saliency is greater than or equal to 1, and it is desired to be much larger than 1 for suitable sensorless control performance. Small signal saliency angle is the angular displacement of the maximum small signal impedance orientation from the rotor reference frame, for example the q-axis of the rotor reference frame. The small signal saliency angle is desired to be constant over the operating range, near zero for example, in order to achieve desired encoderless control performance.

Referring to FIG. 21, a graph showing the small signal saliency on the current vector ( $i_d, i_q$ ) plane for an IPM machine of the related art is depicted as element 300. Contrastingly, FIG. 22 shows the contour plots of small signal saliency of an IPM machine incorporating the component in accordance with the present invention as element 350. As shown in the graph, the resultant saliency is improved and increased as compared to the saliency in the related art machine (FIG. 21).

Referring to FIG. 23, a graph showing the contour plots of small signal saliency angle on the current vector ( $i_d, i_q$ ) plane an IPM machine of the related art is depicted as element 400. Contrastingly, FIG. 24 shows the contour plots of small signal saliency angle of an IPM machine incorporating the component in accordance with the present invention as element 450. As shown in the graph, the resultant wide angular margin by using the component as compared to the related art machine (FIG. 23) depicting the very tight saliency angle.

Referring to FIG. 23, a graph showing the contour plots of small signal saliency angle on the current vector ( $i_d, i_q$ ) plane an IPM machine of the related art is depicted as element 400. Contrastingly, FIG. 24 shows the contour plots of small signal saliency angle of an IPM machine incorporating the component in accordance with the present invention as element 450. As shown in the graph, the resultant wide angular margin by using the component as compared to the related art machine (FIG. 23) depicting the very tight saliency angle.

FIG. 25 shows a graph that depicts speed (%) on a x-axis vs. torque (%) on a y-axis. As shown, when a machine uses the component of the present invention the performance of the machine may reach the upper-left portion (i.e., dark upward pointing arrow) of the graph. That is by employing aspects of the present invention, full torque capability at lower machine speeds is attainable. (For example, an electric machine of the present invention may reach 50% of torque capability at speeds below 10% of the rated speed of the machine. In other embodiments, the electric machine may reach over 75% of torque capability at speeds below 10% of the rated speed of the machine. In still other embodiments, the electric machine may reach over 90% of torque capability at speeds below 10% of the rated speed of the machine. In still other embodiments, the electric machine may reach 100% of torque capability at speeds below 10% of the rated speed of the machine.)

Under aspects of the present invention, the components 10 and the electric machines 100 discussed herein may be used as a traction motor for virtually any vehicle. A vehicle support frame connected to the one or more electric machine 100.

Suitable vehicles for use include, but are not limited to, an off-highway vehicle (OHV), a locomotive, a mining vehicle, electric-motorized railcar, automobiles, trucks, construction vehicles, agricultural vehicles, airport ground service vehicles, fork-lifts, non-tactical military vehicles, tactical military vehicles, golf carts, motorcycles, mopeds, all-terrain vehicles, and the like.

While the embodiments illustrated and described generally herein have shown that the electric machine 100 to be an interior permanent magnet (IPM) machine, other electric machines than those illustrated herein may employ aspects of the present invention including, for example, PMSRM, SRM, and induction machine, and the like. Various embodiments of the rotor circuit component 10 may be used in these various other types of electric machines.

Therefore, in accordance with one aspect of the invention, a rotor component comprises a rotor circuit configured for use with one of an interior permanent magnet (IPM) machine and a synchronous reluctance machine (SRM), the rotor circuit comprising: at least one pole circuit, wherein the at least one pole circuit are made of a conductive, non-magnetic material.

In accordance with another aspect of the invention, an electric machine comprises a rotor core comprising magnetic steel; a stator configured with a plurality of stationary windings therein; a plurality of openings disposed within or on the rotor core; and a rotor circuit configured to introduce saliency based on an orientation of a portion of the rotor circuit in relationship to a pole location of the electric machine, said rotor circuit made of a conductive, non-magnetic material.

In accordance with another aspect of the invention, an electric machine comprises: a rotor core; a stator configured with a plurality of stationary windings therein; a plurality of openings disposed within the rotor core; and a rotor circuit structure comprising at least one pole circuit disposed in a predetermined location, wherein said predetermined location is in range that extends from about a q-axis to about a d-axis of the electric machine.

In accordance with another aspect of the invention, an electric machine comprising: a rotor core; a stator configured with a plurality of stationary windings therein; a plurality of openings disposed within the rotor core; a rotatable shaft therethrough; and a rotor circuit structure comprising at least one loop or ring of a conductive, non-magnetic material, wherein said at least one loop or ring is substantially concentric about a d-axis of the electric machine.

In accordance with another aspect of the invention, an interior permanent magnet (IPM) machine comprises a means for converting electrical energy to rotational energy; and a means for providing increased magnetic saliency at high frequency excitation.

While only certain features of the invention have been illustrated and/or described herein, many modifications and changes will occur to those skilled in the art. Although individual embodiments are discussed, the present invention covers all combination of all of those embodiments. It is understood that the appended claims are intended to cover all such modification and changes as fall within the intent of the invention.

What is claimed is:

1. An electric machine comprising:
  - a rotor core comprising magnetic steel;
  - a stator configured with a plurality of stationary windings therein;
  - a plurality of openings disposed within or on the rotor core;
  - a plurality of permanent magnets disposed in the plurality of openings; and

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a rotor circuit configured to introduce saliency based on an orientation of a portion of the rotor circuit in relationship to a pole location of the electric machine, said rotor circuit made of a conductive, non-magnetic material, wherein a portion of the rotor circuit and the plurality of permanent magnets are disposed in the same plurality of openings.

2. The electric machine of claim 1, wherein the plurality of permanent magnets are disposed in a plurality of rows.

3. The electric machine of claim 1, wherein the electric machine is one of an interior permanent magnet (IPM) machine and a permanent magnet (PM) machine.

4. The electric machine of claim 3, the IPM machine comprising one of a single layer IPM, a multi-layer IPM, and a spoke-type IPM.

5. The electric machine of claim 1, wherein the electric machine comprises a traction motor.

6. The electric machine of claim 1, wherein the rotor circuit comprises a plurality of rotor conductors connected to a plurality of connection elements.

7. The electric machine of claim 6, wherein at least one of the plurality of rotor conductors comprise one of a rotor bar, a multi-stranded bar, a multi-stranded wire, and a litz wire.

8. The electric machine of claim 6, wherein a cross-sectional shape of the plurality of rotor conductors is contoured to fit a shape of the plurality of openings.

9. The electric machine of claim 1, wherein the rotor circuit defines a configuration of at least one of a loop, a shifted loop, a cage, a shifted cage, and combinations thereof.

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10. The electric machine of claim 1, the rotor circuit comprising a plurality of rotor conductors and one or more connection elements, wherein the plurality of rotor conductors are disposed in a plurality of openings adjacent the plurality of permanent magnets.

11. The electric machine of claim 10, further wherein the plurality of rotor conductors is disposed in one of the plurality of openings.

12. The electric machine of claim 1, the rotor circuit comprising at least one pole circuit.

13. The electric machine of claim 12, wherein the at least one pole circuit comprises a plurality of pole circuits.

14. The electric machine of claim 12, wherein a quantity of the at least one pole circuit equals a quantity of poles.

15. The electric machine of claim 1, further comprising a shaft configured to rotate within the electric machine.

16. The electric machine of claim 1, the rotor core further comprising a plurality of laminations.

17. The electric machine of claim 16, the plurality of openings disposed through the plurality of laminations.

18. A vehicle comprising at least one electric machine of claim 1 thereon, said electric machine configured as a traction motor; and

a vehicle support frame connected to said electric machine.

19. The vehicle of claim 18, wherein the vehicle comprises one of an off-highway vehicle (OHV), a locomotive, a mining vehicle, and an electric-motorized railcar.

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